Design of a 24–40 GHz balanced low noise amplifier using Lange couplers

Zhang Zongnan(张宗楠)†, Huang Qinghua(黄清华), Hao Mingli(郝明丽), Yang Hao(杨浩), and Zhang Haiying(张海英)

(Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China)

Abstract: A wide band (24–40 GHz) fully integrated balanced low noise amplifier (LNA) using Lange couplers was designed and fabricated with a 0.15 μm pseudomorphic HEMT (pHEMT) technology. A new method to design a low-loss and high-coupling Lange coupler for wide band application in microwave frequency was also presented. This Lange coupler has a minimum loss of 0.09 dB and a maximum loss of 0.2 dB over the bandwidth from 20 to 45 GHz. The measured results show that the realized four-stage balanced LNA using this Lange coupler exhibites a noise figure (NF) of less than 2.7 dB and the maximum gain of 30 dB; moreover, a noticeably improved reflection performance is achieved. The input VSWR and the output VSWR are respectively less than 1.45 and 1.35 dB across the 24–40 GHz frequency range.

Key words: Lange coupler；balanced; LNA；low loss; pHEMT

DOI: 10.1088/1674-4926/30/4/045001 **PACC:** 7340J **EEACC:** 2570

1. Introduction

Many emerging systems including active-array space-based radars, mobile millimeter-wave communications and handheld imagers are currently in production[1, 2]. The receive circuitry sensitivity is critical to the reception of signals, while the noise and the gain of LNA determines the sensitivity of the total receiver[3]. In addition, the input/output matching and stability of LNA are also critical to the receiver.

The balanced LNA is an attractive candidate for MMIC application such as satellite and base-station transceiver front-ends, because it can present several competitive performances: (1) 3 dB improvement for 1 dB compression point; (2) inherent 50 Ω input/output matching due to the coupler presence; (3) a high degree of stability and reliability. Accordingly, it is employed extensively for millimeter-wave application.

Before the realization of a high performance balanced LNA, there is one issue that must be considered: the Lange coupler will introduce a considerable signal loss, and it is an awful effect because the signal loss before the LNA means the increment of NF.

In this paper, a new method of designing a low-loss and high-coupling Lange coupler was presented, and a balanced LNA was designed. The increment of NF introduced by the Lange coupler is acceptable. Meanwhile, an excellent input/output reflection performance below 1.45 dB across the 24–40 GHz frequency range was achieved.

2. Design of balanced amplifier

The circuit topology of the adopted balanced amplifier structure is shown in Fig. 1.

As shown in Fig. 1, the input coupler with an ideally 3-dB coupling coefficient and a 90° phase difference splits the input signal into two paths, and the two quadrature signal are respectively amplified by the two identical sub-amplifiers in each path, finally the output coupler with an inverted 90° phase shift combines the two signals and deliver them to the output terminal. As a result, the balanced amplifier displays the same gain as the single sub-amplifier. If the impedances of both sub-amplifiers are mismatched, the input coupler will respectively send the reflected signals to the input port and isolated port with a 180° and a 0° phase difference. At the input port, the reflected signal will be canceled; and at the isolated port, the reflected signal will be added and consumed by the terminal resistor. The same case will happen on the output signal. The S-parameters of the whole balanced amplifier can be expressed using the S-parameter of the sub-amplifier as

$$
\begin{aligned}
|S_{11}| &= 0.5\left|S_{11,\mathrm{Amp1}} - S_{11,\mathrm{Amp2}}\right| = 0 \\
|S_{12}| &= 0.5\left|S_{12,\mathrm{Amp1}} + S_{12,\mathrm{Amp2}}\right| = S_{12,\mathrm{Amp1}} \\
|S_{21}| &= 0.5\left|S_{21,\mathrm{Amp1}} + S_{21,\mathrm{Amp2}}\right| = S_{21,\mathrm{Amp1}} \\
|S_{22}| &= 0.5\left|S_{22,\mathrm{Amp1}} - S_{22,\mathrm{Amp2}}\right| = 0.
\end{aligned}
\tag{1}
$$

Thus it can be seen, excellent input and output matching conditions can be achieved in a balanced amplifier configuration and a large increase will occur in the stability or k factor. Hence, this will make it easier to realize a good impedance matching for wide band amplifiers.

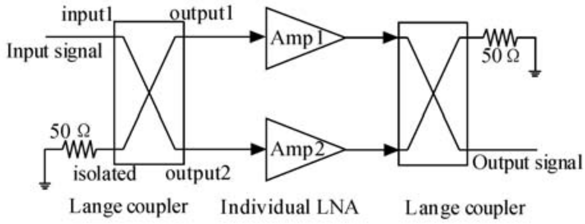

Fig. 1. Circuit topology of the balanced LNA.

† Corresponding author. Email: zongnanzhang@gmail.com

Received 28 September 2008, revised manuscript received 5 November 2008

© 2009 Chinese Institute of Electronics

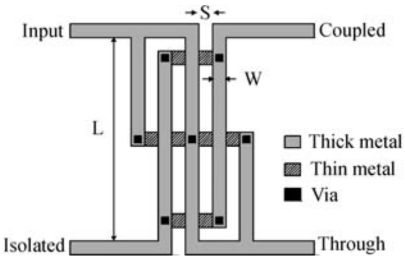

Fig. 2. Schematic of the presented Lange coupler.

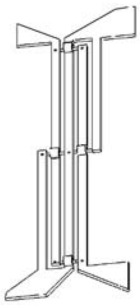

Fig. 3. 3D view of the presented Lange coupler.

Table 1. Substrate parameter in momentum.

	Thickness (μm)	Er / Conductor
Substrate	100	12.8
Thick metal	3.3	0.009 Ω/Sq
Thin metal	0.5	0.06 Ω/Sq

2.1. Design of Lange coupler

To design a wide-band balanced LNA, a low-loss and high-coupling 90 ° coupler which covers a wide band must be firstly realized. The Lange coupler and Wilkinson coupler (branch-line coupler) are commonly used as 90 ° couplers[5, 6]. In this design, the Lange coupler is adopted because it occupies less chip area. The major challenge in the design of the lateral-coupled Lange couplers is how to avoid the inhomogenous and asymmetric nature of the structure, which prohibits the occurrence of even and odd modes, and to compensate the differences in even- and odd-mode phase velocities[7].

As can be seen in Fig. 2, the key dimension of the presented Lange coupler are composed of the coupled line length (L), coupled line width (W), and space between the lines (S). For the Lange coupler design, the space S between the lines relates to the signal coupling, and the coupled line width W is an important consideration for signal loss, while the length L is designed to match the quarter-wavelength of the center frequency. According to the traditional method, the L, W, and S values can be calculated based on computed values of the even- and odd-mode impedances and effective dielectric constants using the assumption of coupled micro-strip lines[9].

The Lange coupler in this work is designed and fabricated with the 0.15 μm pHEMT technology. In this technology, one thin metal layer with a thickness of 0.5 μm and one thick metal layer with a thickness of 3.3 μm are available, and the thin metal layer, i.e. the first metal, is under the thick metal. Generally, compared with the thick metal layer, the thin metal layer shows better precision for a long strip in the fabrication.

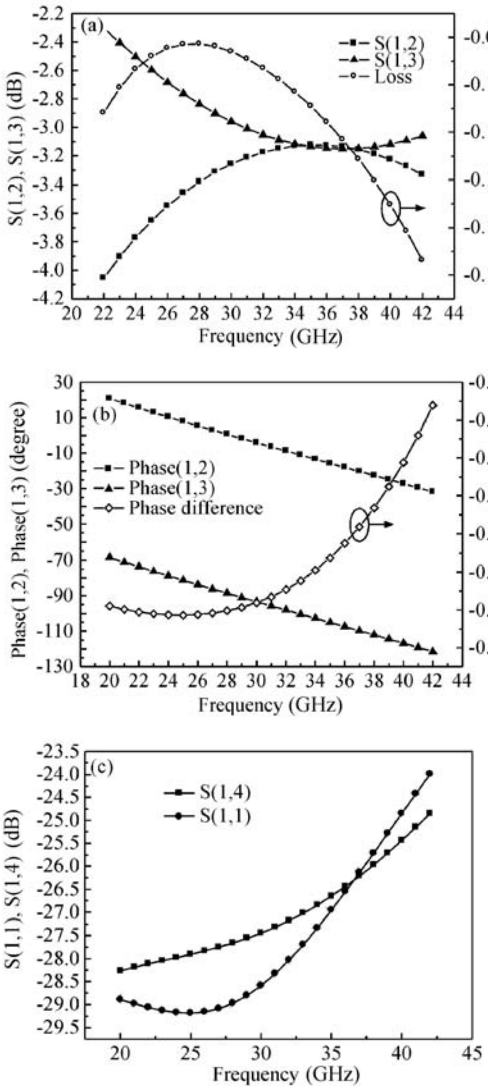

Fig. 4. Simulated results of the presented Lange coupler.

From this point of view, the signal lines of the traditional Lange coupler are mostly designed with the thin metal layer. However, the thin metal layer exhibits a considerable signal loss due to its resistance, which will directly deteriorate NF. The thick metal layer will give us a low signal loss which can almost be ignored. Moreover, observing from the EM simulation, the influence due to the process variation of W and S is acceptable, and a better performance can be achieved by using the thick metal layer as the signal lines and using the thin metal layer as the connecting lines. To avoid MIM capacitance in the crossing between signal line and connecting line, different from the traditional Langer coupler, an air-bridge over the connecting line is designed with the signal line, which is shown in Fig. 3. The EM simulation was completed with the Agilent MOMENTUM. The setting of the substrate parameter is shown in Table 1. The optimized value of L, W and S are 780, 10 and 6 μm, respectively.

The simulated results of the Lange coupler are shown in Fig. 4. Over a wide band (24– 40 GHz), the total signal loss is below 0.16 dB with a coupling amplitude of -3.1 ± 0.6 dB (see Fig. 4(a)), and the phase difference between port 2 and port 3 is below 0.9 ° (see Fig. 4(b)). Moreover the input reflection

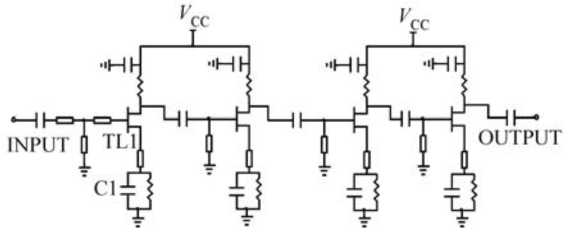

Fig. 5. Circuit topology of the individual LNA in balanced configuration.

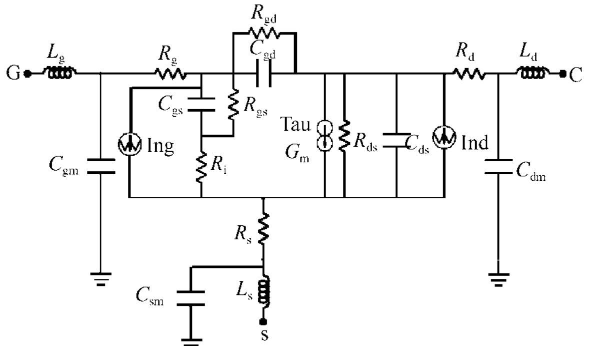

Fig. 6. Noise equivalent circuit model of a pHEMT transistor.

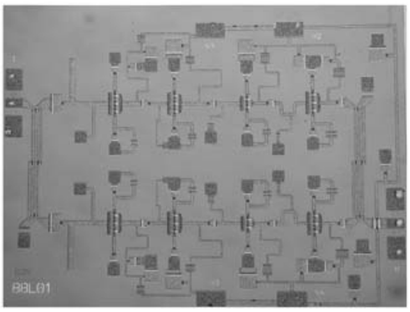

Fig. 7. Photograph of the wideband balanced LNA chip.

S_{11} and isolation S_{14} are both below –24 dB in the desired frequency range.

2.2. Individual LNA design

As shown in Fig. 5, the individual LNA of the balanced amplifier consists of 4-stages. The first and second stage circuit was matched for the optimum NF, while the third and fourth stage was designed for conjugated matching to obtain the largest gain. The noise equivalent circuit model is shown in Fig. 6. It can be easily found that the gate resistor R_g is one of the main sources of the pHEMT noise; hence the gate resistor R_g should be as small as possible, so several parallel pHEMT can be used to reduce the noise. In this design, the first stage and the second stage are designed with 6×20 μm gates. A self-biased structure is applied to bias the pHEMTs, which needs only one power supply for the whole LNA. Four stages LNA are adopted because it can not only get a high gain, but also bring four different resonance frequency points in the circuit. The optimized combination of the four different resonance frequency points can improve the gain flatness and bandwidth. Furthermore, as shown in Fig. 5, the microstrip TL1 at the source node is equivalent to an inductor, and it forms a feedback, which helps to widen the bandwidth[8].

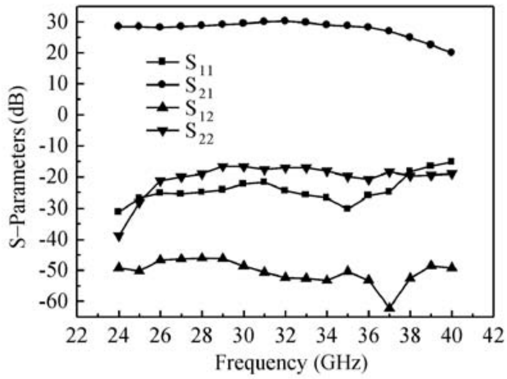

Fig. 8. Measured S-parameters of the presented balanced LNA.

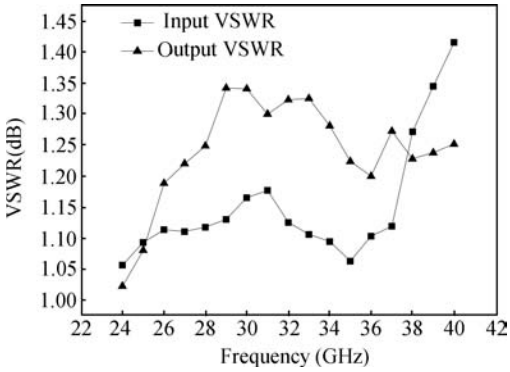

Fig. 9. Input/output VSWR based on the measured S_{11} and S_{22}.

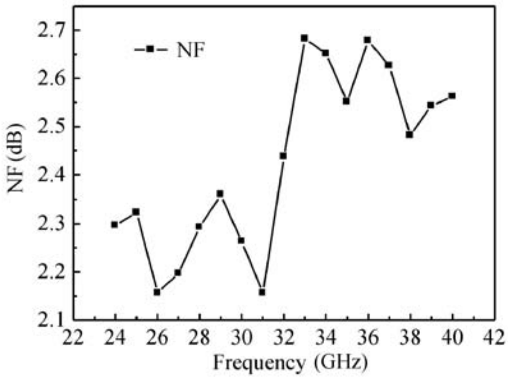

Fig. 10. Measured noise figure.

3. Characterization of the wideband amplifier

A photograph of the fabricated chip is shown in Fig. 7. The amplifier chip size including the probing pads is 2800×2000 μm^2. The chip was measured on-wafer with the coplanar ground-signal-ground (GSG) probes (CASCADE Model 12000), and the DC supply is 3.0 V. Using the HP8722D network analyzer, the S-parameter was measured from 22 to 40 GHz, as shown in Fig. 8. The result shows a peak gain of 30 dB at 32 GHz, and noticeable input and output VSWR are respectively less than 1.45 and 1.35 dB over a range of 22–40 GHz, as shown in Fig. 9. This is contributed to the fact that the VSWR of the balanced amplifier is dictated by the coupler characteristics. The noise performance was tested on AV3985 noise analyzer, and the result is shown in Fig. 10. In the whole operating frequency, the NF is less than 2.7 dB, and the minimum NF of 2.15 dB is achieved at 26 and 31 GHz.

4. Conclusion

A low-loss wideband Lange coupler was presented, and a balanced LNA MMIC with wide bandwidth of 24–40 GHz was successfully designed and fabricated with the presented Lange couplers. As a consequence, the balanced LNA shows a maximum gain of 30 dB and an NF of less than 2.7 dB. Besides, an excellent VSWR performance is achieved, which is obviously improved compared with the individual LNAs[9, 10].

References

[1] Bhattacharya A, Bhavsar M, Thakkar J, et al. Advanced high performance MMICs for satellite transponder. AMPC Proc, 2005

[2] Harvey A R, Cotton F J, Pennington D C, et al. A low noise GaAs MMIC satellite downconverter for the 6 to 4 GHz band. IEEE MTT-S Int Microwave Symp Dig, 1987, 1: 233

[3] Gu Q. Springer Science+Business media. RF System Design Of Transceivers For Wireless Communications, 2005

[4] Eisele K M, Engelbrecht R S, Kurokawa K. Balanced transistor amplifiers for precise wideband microwave application. IEEE Int Solid State Circuits Conf, 1965: 18

[5] Waterman R C, Fabian W, Pucel R A, et al. GaAs monolithic Lange and Wilkinson couplers. IEEE Trans Electron Device, 1981, ED-28(1): 212

[6] Lange J. Interdigitated stripline quadrature hybrid. IEEE Trans Microw Theory Tech, 1969, MTT-17: 1150

[7] Tran M, Nguyen C. Modified broadside-coupled microstrip lines suitable for MIC and MMIC applications and a new class of broadside-coupled band-pass filters. IEEE Trans Microw Theory Tech, 1993, 41(8): 1336

[8] D'Agostino S, Paoloni C. Design of high-performance power-distributed amplifier using Lange couplers. IEEE Trans Microw Theory Tech, 1994, 42(12): 2525

[9] TriQuint Semiconductor, Inc., TGA4507-EPU datasheet, http://www.triquint.com/docs/t/TGA4507/TGA4507-EPU.pdf [access date: 28-Sep-2008]

[10] Mimix Broadband, Inc., XB1005-BD datasheet, http://www.mimixbroadband.com/Data/Document-Library/XB1005.pdf [access date: 28-Sep-2008]